CS 213, Spring 2002
Lab Assignment L6: Dynamic Storage Allocator
Assigned: Tue. Apr. 9, Due: Mon. Apr. 22, 11:59PM

Please see one of us or email `staff-213@cs.cmu.edu` with any questions of concerns. As always, we're here to help.

Introduction

In this lab you will be writing a dynamic storage allocator for C programs, i.e., your own version of the `malloc`, `free` and `realloc` routines. You are encouraged to explore the design space creatively and implement an allocator that is correct, efficient and fast.

Logistics

You may work in a group of up to two people. Any clarifications and revisions to the assignment will be posted on the course Web page.

Hand Out Instructions

The files for this assignment can be retrieved from

`/afs/cs/academic/class/15213-s02/labs/L6/L6.tar`

Once you've copied this file into a (protected) directory, run the command `tar xvf L6.tar`. Fill in your team information in the structure at the beginning of the file `mm.c`. When you have completed the lab, you will hand in only one file (`mm.c`), which contains your solution.

How to Work on the Lab

Your dynamic storage allocator will consist of the following four functions, which are declared in `mm.h` and defined in `mm.c`.

```
int   mm_init(void);
void *mm_malloc(size_t size);
void  mm_free(void *ptr);
void *mm_realloc(void *ptr, size_t size);
```

The `mm.c` file we have given you implements the simplest but still functionally correct malloc package that we could think of. Using this as a starting place, modify these functions (and possibly define other private `static` functions), so that they obey the following semantics:

- `mm_init:` Before calling `mm_malloc` `mm_realloc` or `mm_free`, the application program (i.e., the trace-driven test harness that you will use to evaluate your implementation) calls `mm_init` to perform any necessary initializations, such as allocating the initial heap area. The return value should be -1 if there was a problem in performing the initialization, 0 otherwise.

- `mm_malloc:` The `mm_malloc` routine returns a pointer to an allocated block payload of at least `size` bytes. The entire allocated block should lie within the heap region and should not overlap with any other allocated chunk.

  We will comparing your implementation to the version of `malloc` supplied in the standard C library (`libc`). Since the `libc` malloc always returns payload pointers that are aligned to 8 bytes, your malloc implementation should do likewise and always return 8-byte aligned pointers.

- `mm_free:` The `mm_free` routine frees the block pointed to by `ptr`. It returns nothing. This routine is only guaranteed to work when the passed pointer (`ptr`) was returned by an earlier call to `mm_malloc` or `mm_realloc` and has not yet been freed.

- `mm_realloc:` The `mm_realloc` routine returns a pointer to an allocated region of at least `size` bytes with the following constraints.

  - if `ptr` is NULL, the call is equivalent to `mm_malloc(size)`;
  - if `size` is equal to zero, the call is equivalent to `mm_free(ptr)`;
  - if `ptr` is not NULL, it must have been returned by an earlier call to `mm_malloc` or `mm_realloc`. The call to `mm_realloc` changes the size of the memory block pointed to by `ptr` (the *old block*) to `size` bytes and returns the address of the new block. Notice that the address of the new block might be the same as the old block, or it might be different, depending on your implementation, the amount of internal fragmentation in the old block, and the size of the `realloc` request.

    The contents of the new block are the same as those of the old `ptr` block, up to the minimum of the old and new sizes. Everything else is uninitialized. For example, if the old block is 8 bytes and the new block is 12 bytes, then the first 8 bytes of the new block are identical to the first 8 bytes of the old block and the last 4 bytes are uninitialized. Similarly, if the old block is 8 bytes and the new block is 4 bytes, then the contents of the new block are identical to the first 4 bytes of the old block.

These semantics match the the semantics of the corresponding Linux `malloc`, `realloc`, and `free` routines. Type `man malloc` to the shell for complete documentation.

Heap Consistency Checker.

Dynamic memory allocators are notoriously tricky beasts to program correctly and efficiently. They are difficult to program correctly because they involve a lot of `(void *)` pointer references. You will find it very helpful to write a heap checker that scans the heap and checks it for consistency.

Some examples of what a heap checker might check are:

- Is every block in the free list marked as free?
- Are there any contiguous free blocks that somehow escaped coalescing?
- Is every free block actually in the free list?
- Do the pointers in the free list point to valid free blocks?
- Do any allocated blocks overlap?
- Do the pointers in a heap block point to valid heap addresses?

Your heap checker will consist of the function `int mm_check(void)` in `mm.c`. It will check any invariants or consistency conditions you consider prudent. It returns a nonzero value if and only if your heap is consistent. You are not limited to the listed suggestions nor are you required to check all of them. You are encouraged to print out error messages when `mm_check` fails.

This consistency checker is for your own debugging during development. When you submit `mm.c`, make sure to remove any calls to `mm_check` as they will slow down your throughput. Style points will be given for your `mm_check`. Make sure to put in comments and document what you are checking.

Support routines

The memlib.c package simulates the memory system for your dynamic memory allocator. You can invoke the following functions in `memlib.c`:

- `void *mem_sbrk(int incr)`: Expands the heap by `incr` bytes, where `incr` is a positive non-zero integer and returns a generic pointer to the first byte of the newly allocated heap area. The semantics are identical to the Unix `sbrk` function, except that `mem_sbrk` accepts only a positive non-zero integer argument.
- `void *mem_heap_lo(void)`: Returns a generic pointer to the first byte in the heap.
- `void *mem_heap_hi(void)`: Returns a generic pointer to the last byte in the heap.
- `size_t mem_heapsize(void)`: Returns the current size of the heap in bytes.
- `size_t mem_pagesize(void)`: Returns the system's page size in bytes (4K on Linux systems).

The trace-driven test harness

The `mtest.c` program in the `L6.tar` distribution tests your `mm.c` package for correctness, space utilization, and throughput. The test harness is controlled by a set of *trace files* that are included in the `L6.tar` distribution. Each trace file contains a sequence of allocate, reallocate, and free directions that instruct the test harness to call your `mm_malloc`, `mm_realloc`, and `mm_free` routines in some sequence. The test harness and the trace files are the same ones we will use when we grade your handin `mm.c` file.

The test harness accepts the following command line arguments:

- `-f <tracefile>`: Use one particular `tracefile` for testing instead of the default set.
- `-h`: Print a summary of the command line arguments.
- `-l`: Run `libc` malloc in addition to the student's malloc package.
- `-v`: Verbose output. Print a performance breakdown for each tracefile.
- `-V`: Prints additional diagnostic information as each trace file is processed. Useful during debugging for determining which trace file is causing your malloc package to fail.

Programming Rules

- You are not allowed to change any of the interfaces in `mm.c`.
- You should not invoke any memory-management related library calls or system calls. This excludes the use of `malloc`, `calloc`, `free`, `realloc`, `sbrk`, `brk` or any variants of these calls in your code.
- You are not allowed to define any global or `static` compound data structures such as arrays, structs, trees, or lists in your `mm.c` program. However, you are allowed to declare global scalar variables such as integers, floats, and pointers in `mm.c`.
- For consistency with the `libc` `malloc` package, your allocator must always return pointers that are aligned to 8-byte boundaries. The test harness will enforce this for you.

Evaluation

You will receive **zero points** if you break any of the rules or your code is buggy. Otherwise, your grade will be calculated as follows:

- Correctness (20 points). You will receive full points if your solution passes the correctness tests performed by the test harness (`mtest`). You will receive partial credit for correct implementations of `malloc` and `free` (i.e., you pass the first 9 trace files).

- Performance (35 points). Two performance metrics will be used to evaluate your solution:
  - *Space utilization*: The peak ratio between the aggregate amount of memory used by the test harness (i.e., allocated via `mm_malloc` or `mm_realloc` but not yet freed via `mm_free`) and the size of the heap used by your allocator. The optimal ratio equals to 1. You should find good policies to minimize fragmentation in order to make this ratio as close as possible to the optimal.
  - *Throughput*: The average number of operations completed per second.

  The test harness (`mtest`) summarizes the performance of your allocator by computing a performance index, P, which is a weighted sum of the space utilization and throughput

  $$P = wU + (1 - w) \min\left(1, \frac{T}{T_{libc}}\right)$$

  where U is your space utilization, T is your throughput, and T_{libc} is the estimated throughput of `libc` malloc on your system on the default traces (600 Kops/sec). The index favors space utilization over throughput, with a default of $w = 0.6$.

  Observing that both memory space and CPU cycles are expensive system resources, we adopt this formula to encourage balanced optimization of both. Ideally, the performance index will reach $P = w + (1 - w) = 1$ or 100%. Since each metric will contribute at most w and $1 - w$ to the performance index, respectively, you should not go to extremes to optimize either the memory utilization or the throughput only. To receive a good score, you must achieve a balance between utilization and throughput.

  To get full credit for this part of the lab, you will need to achieve a performance index of 95%. Your score will be calculated by adding .05 to your performance index and multiplying by 35 points. You cannot get more than 35 points for this part of the lab, though.

- Style (10 points). Your code should be readable and well commented. Define macros or subroutines where necessary to make the code more understandable. 5 points will be given for a well written and documented `mm_check` and 5 points will be given for the style of the rest of your code.

Handin Instructions

You will handin your `mm.c` file via a web interface. See the lab webpage for details on how to do this.

You may submit your solution for testing as many times as you wish up until the due date. The web page will list both your best scoring submission and your most recent submission.

When you are satisfied with your solution, then you can officially hand it in. Only the last version you submit will be graded.

When testing your files locally, make sure to use one of the fish machines. This will insure that the grade you get from `mtest` is representative of the grade you will receive when you submit your solution.

Hints

- *Use the* `mtest -f` *option.* During initial development, using tiny trace files will simplify debugging and testing. We have included two such trace files (`short1,2-bal.rep`) that you can use for initial debugging.
- *Use the* `mtest -v` *and* `-V` *options.* The `-v` option will give you a detailed summary for each trace file. The `-V` will also indicate when each trace file is read, which will help you isolate errors.
- *Compile with* `gcc -g` *and use a debugger.* A debugger will help you isolate and identify out of bounds memory references.
- *Understand every line of the malloc implementation in the textbook.* The textbook has a detailed example of a simple allocator based on an implicit free list. Use this is a point of departure. Don't start working on your allocator until you understand everything about the simple implicit list allocator.
- *Encapsulate your pointer arithmetic in C preprocessor macros.* Pointer arithmetic in memory managers is confusing and error-prone because of all the casting that is necessary. You can reduce the complexity significantly by writing macros for your pointer operations. See the text for examples.
- *Do your implementation in stages.* The first 9 traces contain requests to `malloc` and `free`. The last 2 traces contain requests for `realloc`, `malloc`, and `free`. We recommend that you start by getting your `malloc` and `free` routines working correctly and efficiently on the first 9 traces. Only then should you turn your attention to the `realloc` implementation. For starters, build `realloc` on top of your existing `malloc` and `free` implementations. But to get really good performance, you will need to build a stand-alone `realloc`.
- *Use a profiler.* You may find the `gprof` tool helpful for optimizing performance.
- *Start early!* It is possible to write an efficient malloc package with a few pages of code. However, we can guarantee that it will be some of the most sophisticated code you have written so far in your career. So start early, and good luck!